ELECTRICAL ANALYSIS OF PIEZOELECTRIC TRANSFORMERS AND ASSOCIATED HIGH-VOLTAGE OUTPUT CIRCUITS*

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Abstract

Piezoelectric transformers can be useful as compact, high-voltage supplies. At the University of Missouri, the effect of adding output circuits to bipolar piezoelectric transformers is being studied. These piezoelectric transformers produce output voltages in excess of 25 kV from medium-voltage, radio frequency inputs. However, the high output voltage and low output current of these devices can make it difficult to acquire an accurate electrical measurement of the output voltage without affecting the transformer ratio or resonance of the device. This paper will analyze capacitive voltage dividers as a means of diagnostic measurement and Cockcroft-Walton type circuits to increase the voltage multiplication beyond that of the piezoelectric transformer alone.

I. INTRODUCTION

The piezoelectric effect can be a useful mechanism for many actuators or sensors [1], [2]. However, by combining the piezoelectric and inverse-piezoelectric effects of certain materials into a single design, one can create a piezoelectric transformer (PT). PTs can be used to step voltages up or down like a traditional electromagnetic transformer. However, unlike traditional transformers which require mutual magnetic flux linkage between two coils to transform an AC voltage, PTs use the vibrational resonance from the piezoelectric effect to transform the voltage [1], [3], [4]. When an AC voltage is applied between two electrodes across the thickness of a PT, a vibrational resonance is established in an orthogonal direction via the piezoelectric effect. In the non-electroded region, this vibrational resonance causes an electric field that is dependent on the displacement of the material via the inverse-piezoelectric effect. A much smaller output electrode can be placed at the area of greatest displacement to take advantage of this electric field and step up the voltage [5-7]. PTs also have the advantage of compact size, low mass, and high efficiency [3].

While PTs have been investigated as general purpose electrical transformers, there primary role is in the field of certain low power applications [3], [8]. For instance, PTs have been used as gate drivers for MOSFETs and IGBTs as well as high-voltage sources for ozone generation [9], [10]. PTs are also being studied as a high-voltage source for compact active interrogation systems for special nuclear materials [11], [12].

Due to the common use of PTs as high-voltage, low-power sources, many investigations have been performed to optimize their performance and increase their output voltage. A variety of piezoelectric materials as well as multiple transformer geometries have been investigated [3], [13]. As the output voltage of PTs increases, investigations have also been performed to eliminate the problem of surface flashover on the piezoelectric material [14]. Additionally, the use of output circuits attached to the PT to increase voltage or current has also been investigated [15], [16].

This paper presents results from a few different output circuits that were connected to the PT as either a diagnostic or voltage-multiplying output circuit. The

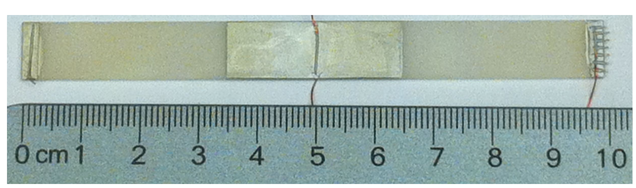

Figure 1. One of the bipolar Rosen-type piezoelectric transformers being used at the University of Missouri.

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output voltage of the bipolar Rosen-type transformer is compared for the different circuits. Additionally, these voltages are compared with theoretical values that were calculated based on the loads' equivalent impedances.

II. EXPERIMENTAL SETUP

A. Piezoelectric Crystals

Piezoelectric materials can convert electrical energy to mechanical energy and vice versa, which makes them useful for high voltage generation. The PT used for these experiments was a bipolar Rosen-type transformer architecture made of lithium niobate ($LiNbO_3$) piezoelectric material. The resonant frequency of this PT is approximately 30 kHz. An applied medium voltage rf signal of approximately 25 V_{max} at the center electrodes establishes a longitudinal resonant vibration, which in turn generates high voltage at each output. Due to the bipolar design, each output is equal in magnitude but 180° out of phase with respect to one another. A differential measurement from end to end describes the output voltage of the PT. Figure 1 shows one of the PTs being investigated at the University of Missouri.

B. X-ray Diagnostic

The PT requires a large load impedance to prevent drawing more current than the PT can supply. Consequently, even measurement with high-impedance voltage probes is difficult as they pull down the output voltage. To solve this problem, an x-ray diagnostic was developed to accurately measure the voltage generated at the output terminal of the transformer without introducing a low load impedance.

The x-ray diagnostic is based upon measuring a bremsstrahlung x-ray spectrum. This bremsstrahlung spectrum has a maximum energy equal to the peak voltage generated by the PT. Atomically sharp field-emitting structures made of platinum-iridium wire were attached to one end of the PT using silver paint, while a tungsten target was biased at the voltage of the opposite end of the PT. Because the ends of the PT are 180° out of phase, field-emitted electrons are accelerated across the gap during the appropriate voltage half-cycle. During the opposite voltage half-cycle, the electric field is not oriented such that electrons are pulled from the field-emitting structures. Thus, this diagnostic acts as an electron beam diode that generates bremsstrahlung x-rays when the electrons impact the target.

However, due to the self-generated fields along the surface of the PT, the electron beam has a tendency to bend upward at a slight angle. This is problematic when trying to align the field-emitting structures with the target. To resolve the issue of a high percentage of electrons not hitting the target, a focusing device was designed. This device used a grounded wire mesh in a convex shape near the field-emitting structures such that the electron beam stayed in a straight line with respect to the PT. The open-area fraction of the wire mesh was approximately 30% with a 30 mm radius of curvature. A diagram of the PT with the focusing device and ray traced electrons can be seen in Figure 2.

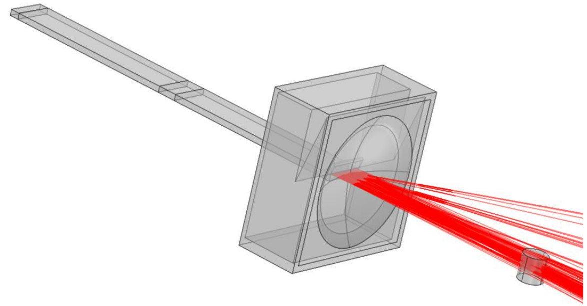

Figure 2. Diagram of the PT and focusing device with ray-traced electrons accelerating toward the target.

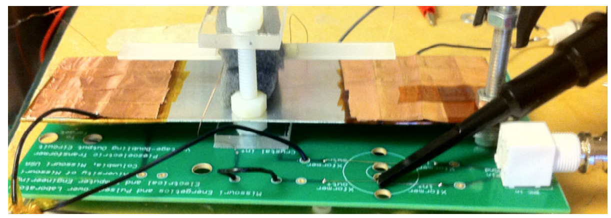

Figure 3. Picture of the capacitive divider circuit with the PT.

C. Capacitive Voltage Divider

The x-ray diagnostic was limited to operation in a vacuum chamber due to the short mean free path of electrons at atmospheric pressure. A capacitive voltage divider was created to allow measurement of the PT output voltage at atmospheric pressure. However, due to the required high impedance, the equivalent capacitance had to be extremely low.

The capacitive divider utilized the output electrode of the crystal and a copper tape electrode across a 15 mm air gap as the low-capacitance, high-voltage side of the divider. The second capacitance was formed between an aluminum ground plane and the copper tape with a kapton tape dielectric of 0.6 mm. This configuration was done on both ends of the PT to achieve a differential measurement. A photograph of the capacitive divider can be seen in Figure 3.

To calibrate the capacitive divider, an inductor-capacitor (L-C) resonant circuit was used. By connecting a 2.8 mH inductor in series with each of the capacitances, the resonant frequency of the L-C circuit could be determined. From that resonant frequency, the

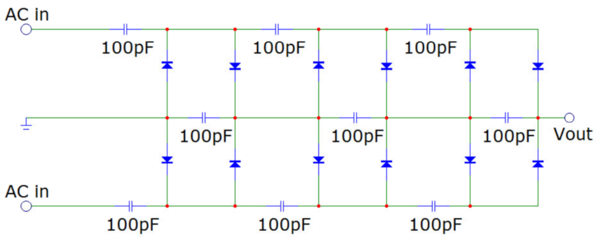

Figure 4. Three-stage, full-wave Cockcroft-Walton circuit.

capacitance could be calculated using (1). It was determined that the capacitance values were approximately 250 fF and 270 pF, creating an approximately 1,000 times divider for each side of the PT.

$$f = \frac{1}{2\pi LC} \tag{1}$$

D. Cockcroft-Walton Output Circuit

In order to further increase the output voltage, a Cockcroft-Walton (CW) circuit was attached to the PT. This circuit converts AC to DC and can be implemented in multiple stages to further multiply the voltage. The circuit schematic for a three-stage CW circuit can be seen in Figure 4. The theoretical output voltage from a CW circuit with ideal diodes can be calculated as shown in (2), where V_{out} is the output voltage, n is the number of stages, and V_{in} is the input voltage from one side. For this circuit, 100 pF capacitors were used.

$$V_{out} = 2nV_{in} \tag{2}$$

IV. RESULTS

Each of the loads to the PT discussed in the previous section were tested. A summary of the approximate load impedances for each load and the corresponding output voltages can be seen in Table 1. Table 1 shows that as the approximate equivalent load impedance went down, so did the output voltage from the PT. The x-ray diagnostic yielded the highest voltage from the PT at approximately

Table 1. Summary of approximate load impedances with corresponding output voltages.

Load Attached to PT	Approximate Load Impedance (MΩ)	Output Voltage (kV)
X-ray Diagnostic	800	33
Capacitive Divider	(0.839 - j20.5)	12
3-Stage Cockcroft-Walton Circuit	5.3	2.9

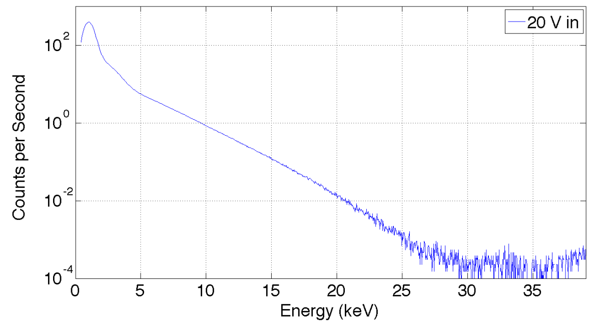

Figure 5. Bremstrahlung x-ray spectrum for the bipolar Rosen-type transformer operated at approximately 30 V_{max}, 30.8 kHz input.

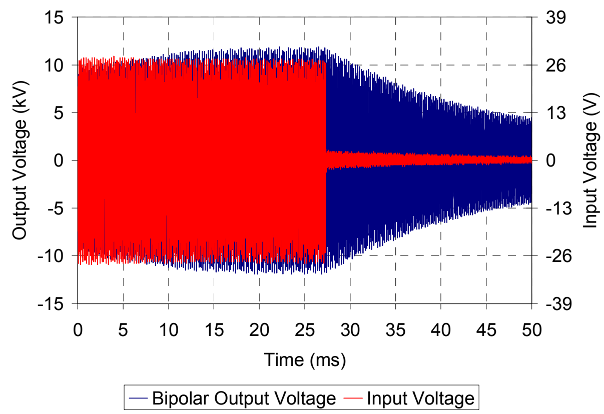

Figure 6. Input and output voltage traces for the PT when connected to the capacitive divider.

33 kV, while the capacitive voltage divider and three-stage CW circuit had output voltages off 12 kV and 2.9 kV, respectively.

A bremsstrahlung spectrum for the PT operated at approximately 30 V_{max}, 30 kHz input can be seen in Figure 5. The endpoint of the x-ray spectrum is at approximately 33 keV which directly corresponds to the peak PT output voltage of 33 kV. The load impedance for the x-ray diagnostic was determined empirically to be approximately 800 MΩ.

Input and output voltage traces for the capacitive divider are shown in Figure 6. For an input voltage of 26 V_{max}, the PT had an output voltage of approximately 12 kV. The capacitive divider had an imaginary component of -20.5 MΩ that was based on the equivalent capacitance of 270 fF at an operating frequency of 30.8 kHz. There was also assumed to be a resistive component of the impedance from the air gap in parallel with the capacitance. This resistance was assumed to be approximately 500 MΩ. When combining these impedances in parallel, the result was (0.839 – j20.5) MΩ.

Results for a single-stage and three-stage CW circuit are shown in Figure 7. The output voltage for the single-stage CW circuit attached to the PT was only 2.4 kV_{DC}. This is due to the significantly lower load impedance with

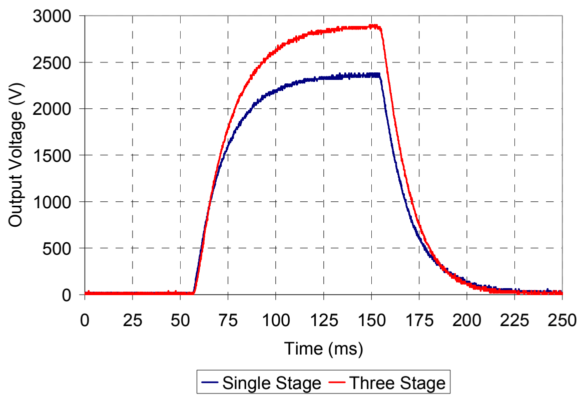

Figure 7. Voltage output for a single-stage and three-stage CW circuit attached to the PT.

respect to the x-ray diagnostic and the capacitive divider. The load impedance of the three-stage CW circuit was determined to be approximately 5.3 MΩ based on the output current and voltage measurements. The output of the three-stage CW circuit was 2.9 kV_{DC}. The three-stage CW circuit should have been approximately 7.2 kV_{DC}. However, as more stages were added to the circuit, the load impedance dropped. This drop in load impedance also lowered the output voltage from the PT that was supplying the CW circuit.

Based on the equivalent load impedances for each of the circuits that were attached to the PT, calculations were performed to determine the variation between theoretical and experimental results. These calculations were based upon the nonlinear material constants for $LiNbO_3$ and the equations of elastic motion with piezoelectric effects. The transformer ratios from the calculations for each load are shown in Figure 8. Although the calculated results for the x-ray diagnostic and the three-stage CW circuit match the experimental results, the capacitive divider did not perform as well in experiments as it did in calculations. This could be due to additional stray capacitance altering the 270 fF divider. The calculated deviation from the resonant frequency of less than 5%, or 1.5 kHz at f_0=30

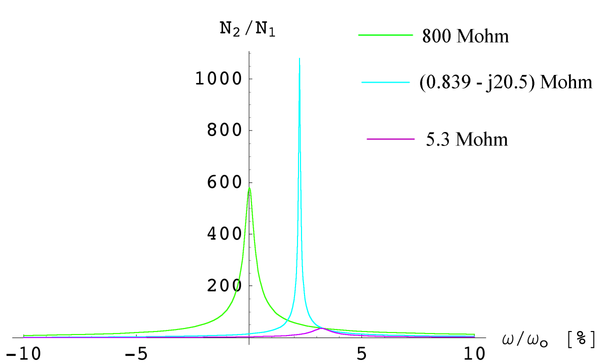

Figure 8. Calculated PT transformer ratios for different load impedances.

kHz, was also noted in experimentation. The experimental operating frequency did not shift more than approximately 150 Hz for each experiment. However, that could be due to some of the assumptions made for the equivalent load impedances during the calculations.

V. CONCLUSIONS

Various output circuits have been tested at the University of Missouri to determine their effects on the output voltage of a lithium niobate, bipolar Rosen-type piezoelectric transformer. It was determined that decreasing load impedance, even by a small amount, led to a significant decrease in output voltage from the PT. Based on experimental and calculated results, it appears as though a load impedance of greater than 500 MΩ is needed to prevent significant decreases in the output voltage from the PT. Therefore, all attempts at voltage multiplying output circuits should utilize only high-impedance components in order to maintain the high PT output voltage for multiplication.

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